Diamond Lake water quality monitoring 2006: data quality assessment, database description, and water quality assessment.

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Introduction

Diamond Lake is a large naturally productive lake in the Cascade Mountains of eastern Douglas County, Oregon (Eilers et al. 2001). In 1998, the lake was placed on Oregon's 303(d) list as water quality impaired for excess algae and high pH values. These water quality problems have impacted recreation, human health, local economic vitality, and downstream water quality. Most notably, the lake has experienced dense summer blooms of *Anabaena sp.*, a cyanobacteria species known to produce toxins. Toxins produced by *Anabaena sp*. have been detected in the lake at concentrations harmful to human health and have led to periodic closures of the lake to public access.

A total maximum daily load (TMDL) assessment, conducted by the Oregon Department of Environmental Quality (ODEQ) and JC Headwaters (Turner et al. 2006), implicated food web changes for the recent dominance of *Anabaena sp*., high pH values, and low hypolimnetic dissolved oxygen concentrations in the lake. Specifically, the introduction of Tui chub (*Gila bicolor*) into the food web has had a significant impact on the lake water quality and the trout fishery through their efficient consumption of large zooplankton and zoobenthos.

As a result of the TMDL assessment, the ODEQ, the Umpqua National Forest, and the Oregon Department of Fish and Wildlife (ODFW) are attempting to reset the food web structure to promote better water quality. All fish in the lake were intentionally killed during September, 2006 with rotenone, a compound that inhibits cellular respiration. During the spring or early summer of 2007, fingerling and adult trout will be stocked into the lake for recreational and economic purposes. Since small trout are also zooplanktivores, they can potentially impact water quality along the same pathways as Tui chub. The number of fingerlings stocked is intended to be at a level that will allow water quality standards to be met. JC Headwaters Inc. has proposed a "Fish Stocking Index" (Eilers 2003) that can be used to evaluate the impact of fish stocking levels on Diamond Lake's water quality.

The Center for Lakes and Reservoirs at Portland State University was employed to study the water quality of Diamond Lake in 2006. This report is partial fulfillment of contract 06-CR-11061503-015 between the Center for Lakes and Reservoirs and the USDA Forest Service, Umpqua National Forest. There are three sections to this report: 1) an assessment of the quality of data collected, 2) a description of the database used to store the information, and 3) an evaluation of water quality trends with reference to the fish stocking index parameters.

Section 1. Diamond Lake water quality monitoring data quality assessment

This section is an assessment of the quality of data collected during five sampling events by the Center for Lakes and Reservoirs at Portland State University in 2006. In situ multiparameter sonde measurements, chemical grab samples, biological samples, Secchi disk transparency, and staff gauge readings were collected. Accuracy, precision and completeness of the data were evaluated when possible.

In situ multiparameter sonde data

Sampling events were conducted on June 27th, July 17th, August 29th, September 26th, and October 31st, 2006. Temperature, dissolved oxygen, conductivity, and pH were measured in situ

with either a Hydrolab DS5 multiparameter sonde or a Hydrolab Quanta multiparameter sonde. Measurements were made at the Diamond Lake Deep site (DLA) and the Lake Creek Outlet site (LCO) during all sampling events, and at the Silent Creek Bridge (SIB) and Short Creek (SHC) sites during the July 17, 2006 sampling event. In situ data were graded according to the Oregon Department of Environmental Quality's Data Quality Matrix (DEQ 2004). The definitions of data quality levels are:

- A+ – Data of known Quality; collected by DEQ; meets QC limits established in the QAPP.
- A – Data of known Quality; submitted by entities outside of DEQ; meets QC limits established in a DEQ-approved QAPP.
- B – Data of known but lesser Quality; data may not meet established QC but is within marginal acceptance criteria; or data value may be accurate, however controls used to measure Data Quality Objective elements failed (e.g., batch failed to meet blank QC limit); the data may be useful in limited situations or in supporting other, higher quality data.
- C – Data of unacceptable Quality; data are discarded (Void) typically in response to analytical failure.
- D – Incomplete data; no sample collected or no reportable results, typically due to sampling failure.
- E – Data of unknown quality or known to be of poor quality; no QA information is available, data could be valid, however, no evidence is available to prove either way. Data is provided for Educational Use Only.
- F – Exceptional Event; "A" quality data (data is of known quality), but not representative of sampling conditions as required by the project plan.(e.g., a continuous water quality monitor intended to collect background environmental conditions collects a sample impacted by a fire that created anomalous conditions to the environment).

Accuracy

Accuracy of in situ sonde dissolved oxygen data was evaluated through comparison with Winkler titrations on a subset of measurements. The accuracy criterion of 0.2 mg/l for grade "A" dissolved oxygen data was met during all sampling events (Figure 1). Accuracy of pH was evaluated through comparison with a calibrated Orion pH meter. The accuracy criterion of 0.2 pH units for grade "A" was met on only the last sampling event (Figure 1). Grade "B" quality pH data (accuracy < 0.5 pH units) were collected on the fourth sampling event. Grade "C" quality pH data were collected during the first three sampling events rendering the pH data for those dates unusable. It was discovered after the fourth sampling event that the sonde's low ionic strength reference had a bubble in it. This bubble allowed calibration while the sonde was upside-down (the normal calibration position), however, when turned right-side up, (the normal operation position) the bubble rose and affected the calibration. A different multiparameter sonde was used during the fifth sampling event which rectified the problem. pH 7 and pH 10 calibrated Orion pH measurements of grab samples were conducted during all sampling events and will be used to fill in the data gap. Conductivity accuracy was assured by daily calibration with 141µS/cm conductivity standard. Temperature was assumed to be accurate to manufacturer's specifications (± 0.1ºC).

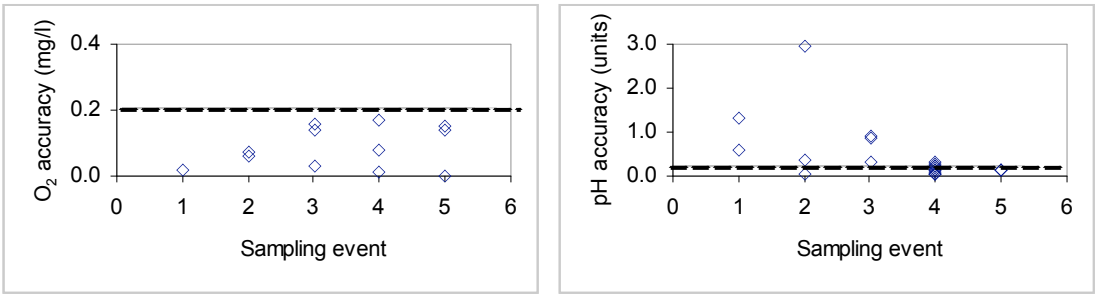

Figure 1. Multiparameter sonde dissolved oxygen and pH accuracy by sampling event. Dissolved oxygen accuracy was assessed by comparison with Winkler titrations of grab samples. pH accuracy was assessed by comparison with Orion pH meter measurements of grab samples. Dashed lines are accuracy targets for "grade a" data.

Precision

Precision of in situ sonde measurements was assured through equilibration of the sensors at each depth for at least 1.5 minutes. Precision was evaluated through comparison of up- and down-cast profile measurements. Conductivity, temperature, and dissolved oxygen precision met the criteria for grade "A" data (Figure 2). pH did not meet precision criteria on the first two sampling events for the reasons outlined in the accuracy discussion.

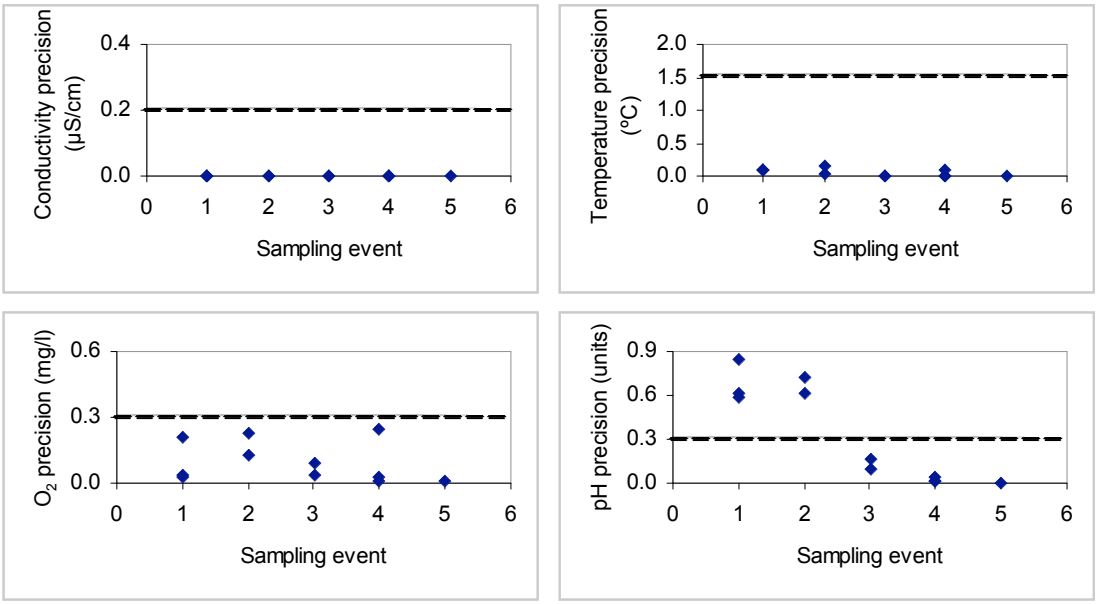

Figure 2. Multiparameter sonde measurement precision by parameter and sampling event. Precision was assessed through comparison of up- and down-cast profile measurements. Dashed lines are precision targets for "grade a" data.

Completeness and grades of in situ multiparameter data

Temperature, conductivity, and dissolved oxygen multiparameter data all met the ODEQ's criterion for grade "A" quality during all sampling events (Table 1). The completeness, or the percentage of data collected that was intended to be collected, was 100% for those parameters. In situ multiparameter pH data met quality targets on only one sampling event and therefore completeness was only 20%.

Table 1. In situ data quality grades by sampling event.

Sampling event	Temperature	Conductivity	D.O.	pH
6/27/06	A	A	A	C
7/17/06	A	A	A	C
8/29/06	A	A	A	C
9/26/06	A	A	A	B
10/31/06	A	A	A	A

Chemical data

Chemical samples from the five sampling events were submitted to the Corvallis Cooperative Analytical Laboratory (CCAL). Primary field samples, one field duplicate sample and one field blank sample were submitted for each sampling event. Nanopure distilled water from the Portland State University Center for Lakes and Reservoirs Water Quality Laboratory was used for field blank analyses. CCAL analyzed laboratory replicate samples for a subset of the samples for most of the parameters as a check on laboratory precision. Accuracy of laboratory measurements was assured by CCAL through use of APHA methods (APHA 2005). Accuracy of field measurement was assumed if field blank samples were less than CCAL's minimum levels of quantification. Precision was evaluated through comparison of field replicate samples. Relative percent difference (RPD) between field replicates of less than 15% was considered good precision. For parameters consistently measured near the method detection limit (within 5 times the detection limit), the relative error ratio (RER) was used as a measure of precision rather than the RPD. Data were graded pass/fail for each parameter and sampling event on the basis of meeting both the accuracy and precision criteria.

Accuracy

Field blank samples were below CCAL's minimum levels of quantification for all parameters on all dates except for dissolved organic carbon (DOC) and total organic carbon (TOC) on the first four sampling dates (Figure 3). In addition, blank DOC values were higher than blank TOC values indicating that there was carbon contamination from the filters. Filters were acid washed and rinsed with Nanopure deionized water prior to the fifth sampling event. This resulted in lower, yet still detectable concentrations of DOC. During one sampling event each, field blank measurements of unfiltered total phosphorus (UTP), soluble reactive phosphorus (OP), nitrate plus nitrite nitrogen (NO3) and unfiltered total nitrogen (UTN) were above method detection limits, yet below minimum levels of quantification (Figure 3). Total dissolved solids concentrations in blanks are not displayed in Figure 3, but were below detection limits during all sampling events.

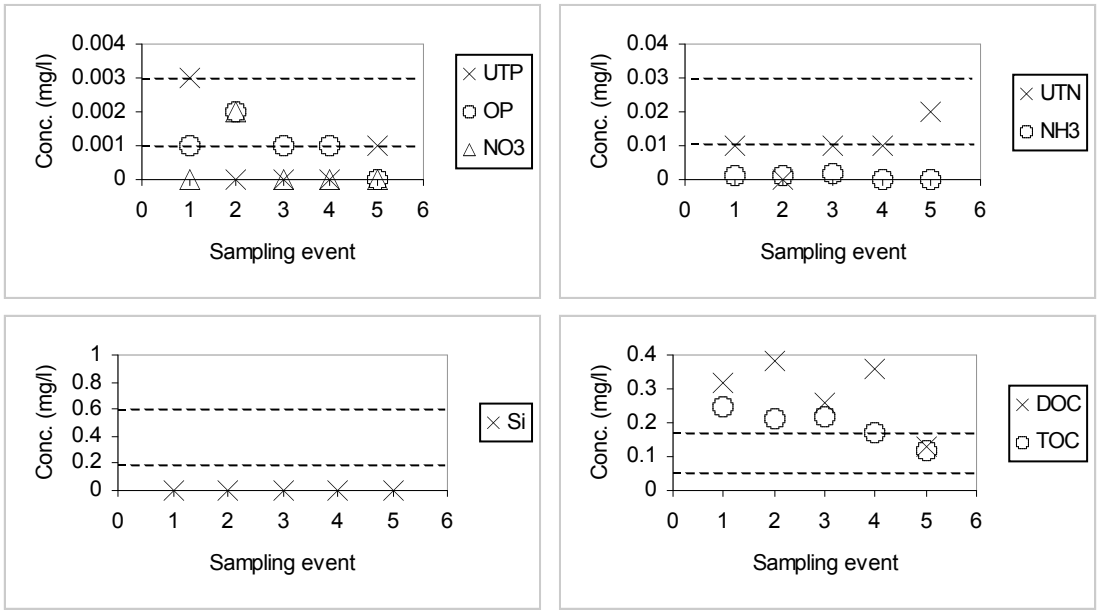

Figure 3. Field blank chemical analyses results by sampling event. CCAL method detection limits are represented by the lower dashed lines in each panel. CCAL minimum levels of quantification are represented by the upper dashed lines in each panel. UTP=unfiltered total phosphorus, OP=soluble reactive phosphorus, NO3=nitrate+nitrite-nitrogen, NH3= ammonia-nitrogen, Si=dissolved silica, DOC=dissolved organic carbon, and TOC=total organic carbon.

Precision

Laboratory precision targets were met for all parameters except total organic carbon during the fifth sampling event (Figure 4). Field precision targets were met for all parameters except total dissolved solids during the third sampling event (Figure 5).

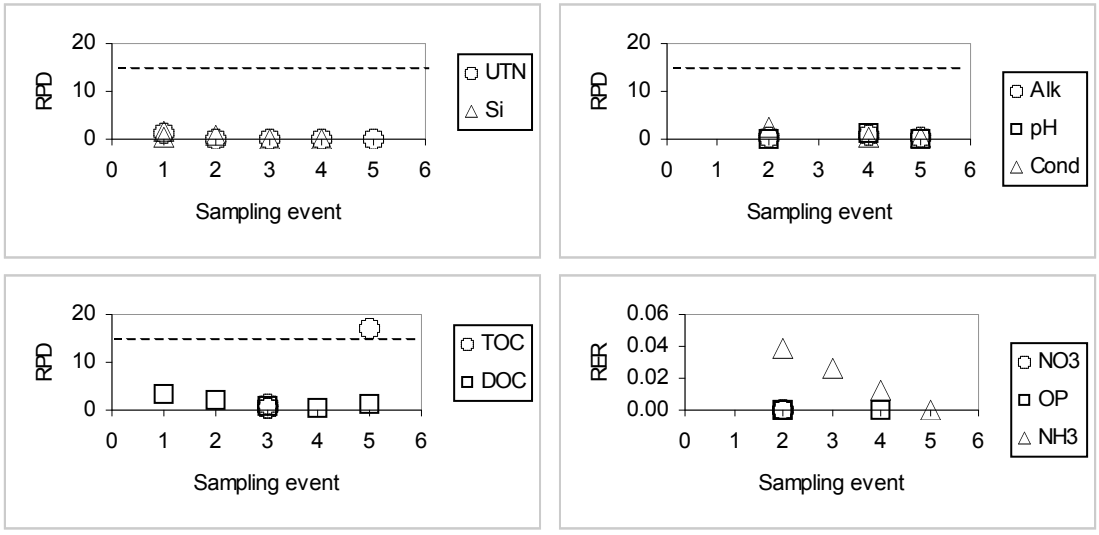

Figure 4. Relative percent differences (RPD) and replicate error ratios (RER) between laboratory replicate samples by sampling event. Dashed lines are at 15% RPD criteria. RER ratios below 2 are considered good. Laboratory replicates were not conducted for all parameters on all sampling events. Parameter codes are as in Figure 3.

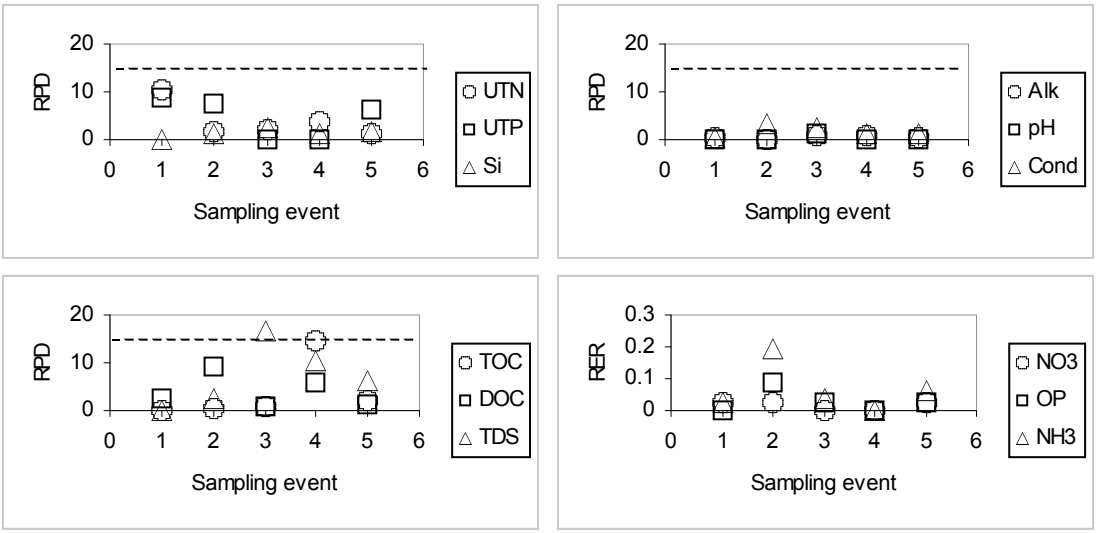

Figure 5. Relative percent differences (RPD) and replicate error ratios (RER) between replicate field grab samples by sampling event. Dashed lines are at 15% RPD criteria. RER ratios below 2 are considered good. Parameter codes are as in Figure 3.

Completeness and grades of chemical data

Samples were collected and submitted from all intended depths and sites so completeness was 100% for all parameters other than TOC, DOC, and TDS (Table 2). TOC was complete and of passing grade for 0% of the events, DOC was complete for 20% of the events, and TDS was complete for 80% of the events.

Table 2. Pass (P) and fail (*F*) grades of chemical grab samples submitted to CCAL by parameter and sampling event. "(b)" indicates failing grade because of high blank values, "(lp)" indicates lab precision failure, and "(fp)" indicates field precision failure.

Sampling event	UTP	UTP	OP	NO3 -N	NH3 -N	TOC	DOC	TDS	Si
6/27/06	P	P	P	P	P	*F (b)*	*F (b)*	P	P
7/17/06	P	P	P	P	P	*F (b)*	*F (b)*	P	P
8/29/06	P	P	P	P	P	*F (b)*	*F (b)*	*F (fp)*	P
9/26/06	P	P	P	P	P	*F (b)*	*F (b)*	P	P
10/31/06	P	P	P	P	P	*F (lp)*	P	P	P

Biological data

Chlorophyll-a, phytoplankton species, and zooplankton species samples were collected and submitted to analysis laboratories. The quality of chlorophyll-a data was evaluated through the relative percent difference between blind replicate samples submitted during each sampling event. Accuracy and precision of phytoplankton species counts were evaluated through assessing the similarity of blind split samples. Accuracy and precision of zooplankton data were assessed through the similarity of split samples.

Chlorophyll-a

Blind replicate chlorophyll-a samples were used to evaluate the precision of estimates. Replicate samples were decanted from a single Niskin bottle at the DLA site at each depth during each sampling event into 125 ml dark HDPE bottles containing magnesium carbonate for preservation. Bottles were labeled to preclude identification of the replicates by the analyst in the laboratory. The relative percent difference between replicates was less than 15 percent for all replicate sets, and less than 10 percent for all but one replicate set (Table 3). In addition to the replicates collected from single Niskin grabs, replicate Niskin grab samples were collected from 1 m during the August 29th sampling event to evaluate precision between grabs. The relative percent difference between the average concentrations of each sample was six percent.

The accuracy of chlorophyll-a concentration estimates was assured through proper calibration of the Aquatic Analysts' laboratory fluorometer with certified standards.

Table 3. Relative percent difference between replicate chlorophyll a samples.

			Chlorophyll (µg/l)		
Site	Date	Depth (m)	Split 1	Split 2	RPD
DLA	6/27/2006	1	8.0	8.0	0.0
DLA	6/27/2006	8	35.0	34.0	2.9
DLA	6/27/2006	11	42.0	41.0	2.4
DLA	7/17/2006	1	8.0	8.8	9.5
DLA	7/17/2006	8	18.2	17.5	3.9
DLA	7/17/2006	11	20.4	20.4	0.0
DLA	8/29/2006	1	16.1	17.5	8.3
DLA	8/29/2006	7	20.0	20.4	2.0
DLA	8/29/2006	10	20.4	20.4	0.0
DLA	9/26/2006	1	20.4	21.8	6.6
DLA	9/26/2006	5	19.0	20.4	7.1
DLA	9/26/2006	10	22.0	20.4	7.5
DLA	10/31/2006	1	64.0	61.0	4.8
DLA	10/31/2006	6	64.0	59.0	8.1
DLA	10/31/2006	11	67.0	59.0	12.7

Phytoplankton species composition and abundance

Because the true taxonomic composition and species abundance within the phytoplankton community cannot be known, accuracy can not be estimated though comparison with standards. In addition, since these measures are multivariate, traditional measures such as relative percent difference between replicate samples are not sufficient for estimating precision. The similarity of replicate samples has been used to estimate the similarity of samples to the community from which they are drawn (Cao et al. 2002). Blind split phytoplankton samples were used to evaluate quality of the phytoplankton samples both in terms of composition and abundance. We used both species composition-based and species abundance-based similarity indices, although species abundance measures are most relevant to the indices of water quality health. EstimateS software (Colwell 2005) was used to calculate all similarity indices. The Sorenson index was used to evaluate species composition similarity, and Bray-Curtis, Morisita-Horn, and Chao-Sorenson were used to evaluate species abundance similarity.

Species composition (presence/absence of species) similarity between the blind split samples ranged from 41 percent during the October sampling event to 82 percent during the July

sampling event (Table 4). These low similarity values suggest that, with the analytical protocols currently in place, the utility of presence/absence data as a metric of community change is limited. Similarity values were much better when species abundance is taken into account. The Bray-Curtis abundance-based similarity index ranged from 72 to 93% similarity between split samples (Figure 6). The other abundance based indices indicated even better similarity between split samples.

Table 4. Number of phytoplankton species identified in each blind split sample, in either of the splits, and shared between the splits. The Sorenson similarity index is a species presence/absence index. Sample pairs with an index value of one means each sample has the same species composition, a value of zero means there are no shared species between sample pairs.

		Number of Species				Sorensen
Date	Depth (m)	Split 1	Split 2	Either	Shared	similarity index
6/27/2006	8	17	16	24	9	0.55
7/17/2006	11	27	29	33	23	0.82
8/29/2006	1	9	10	15	4	0.42
9/26/2006	10	14	9	16	7	0.61
10/31/2006	6	24	15	31	8	0.41

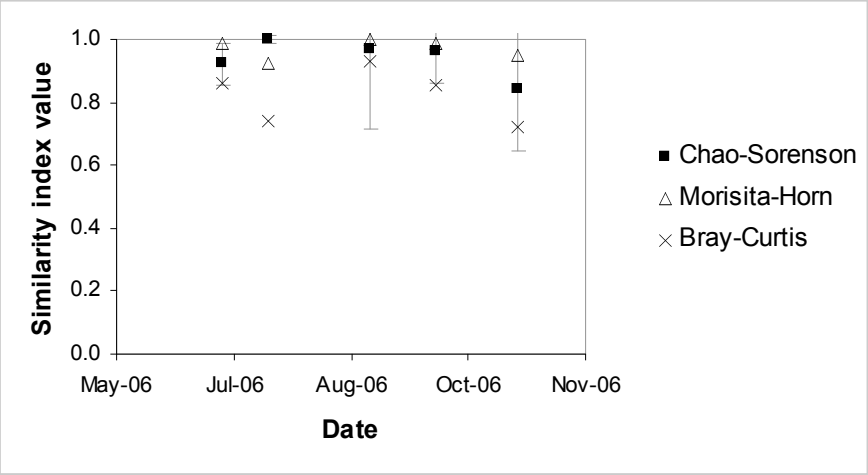

Figure 6. Abundance based similarity index values for blind split phytoplankton species counts. Whiskers represent standard deviations calculated for the Chao-Sorenson similarity index. The Bray-Curtis average similarity is 0.83 with a range 0.72-0.93.

Zooplankton species composition

Zooplankton were collected during each sampling event with an 20-cm Wisconsin (Puget) style 65 µm-mesh zooplankton net. Vertical tows were from 10 m to the surface during the July through October sampling events, and from 11.5 m to the surface during the June sampling event. Samples were split on shore with a Folsom plankton splitter and preserved with a final ethanol concentration of 30 percent for splits sent to ZP's taxonomic service and to 70 percent for splits submitted to PhycoTech (per each lab's protocols). The similarity between split samples was calculated using the Sorenson index, a presence/absence based similarity index, and the Bray-Curtis similarity index, an abundance based similarity index. Similarity between samples was low, especially when calculated at the species level (Table 5). Similarity at the genus level was considerably better (Table 5). Low similarity was expected after the rotenone

treatment since zooplankton abundance and diversity was extremely low and consisted of small rotifers, which are more difficult to accurately identify than large zooplankton.

Table 5. Similarity between zooplankton split samples. Similarity index values range from zero to one with zero meaning no similar species and one meaning all species are shared.

				Species based		Genus based	
Date	Number of taxa observed by ZP's	Number of taxa observed by Phycotech	Observations shared between taxonomists	Sorensen similarity index	Bray-Curtis similarity index	Sorensen similarity index	Bray-Curtis similarity index
6/27/2006	19	9	3	0.2	0.4	0.6	0.7
7/17/2006	23	12	5	0.3	0.4	0.6	0.6
8/29/2006	18	8	3	0.2	0.7	0.6	0.8
9/26/2006	5	2	1	0.3	0.4	0.3	0.4
10/31/2006	16	4	2	0.2	0.5	0.2	0.5

Section 2. Database description

A Microsoft Access database (diamond 2006.db1) was created to store the data. The database consists of a sampling event table, seven results tables, a sonde quality assurance value table, a zooplankton tow summary tables, a chemistry methods table, and a site detail table (Figure 7). Results tables include chlorophyll-a, phytoplankton, Secchi transparency, zooplankton, chemistry, sonde, and staff gage. Sampling events are defined by researcher, date, site, and depth fields and are listed in the sampling events table. These four fields are used to link the sampling events table to each of the results tables. The zooplankton and Secchi results tables are linked to the unique events table by researcher, date, and site fields. Chemistry sample quality assurance sample types are listed within the chemistry table and include primary, field replicate, lab replicate. Sonde quality assurance sample types are listed within the sonde results table include whether a sample is the final measure at a depth and if the sample is from the downcast (primary sample), or the upcast. Sonde accuracy-check values are listed in the sonde quality assurance table. Because sonde depths were recorded to the hundredths of a meter, sonde depth may not always match with chemistry and chlorophyll a sample depth which are to the nearest half meter. Sonde values were therefore linked to the other value tables through a calculated field in the sonde values table defined as the nearest half meter.

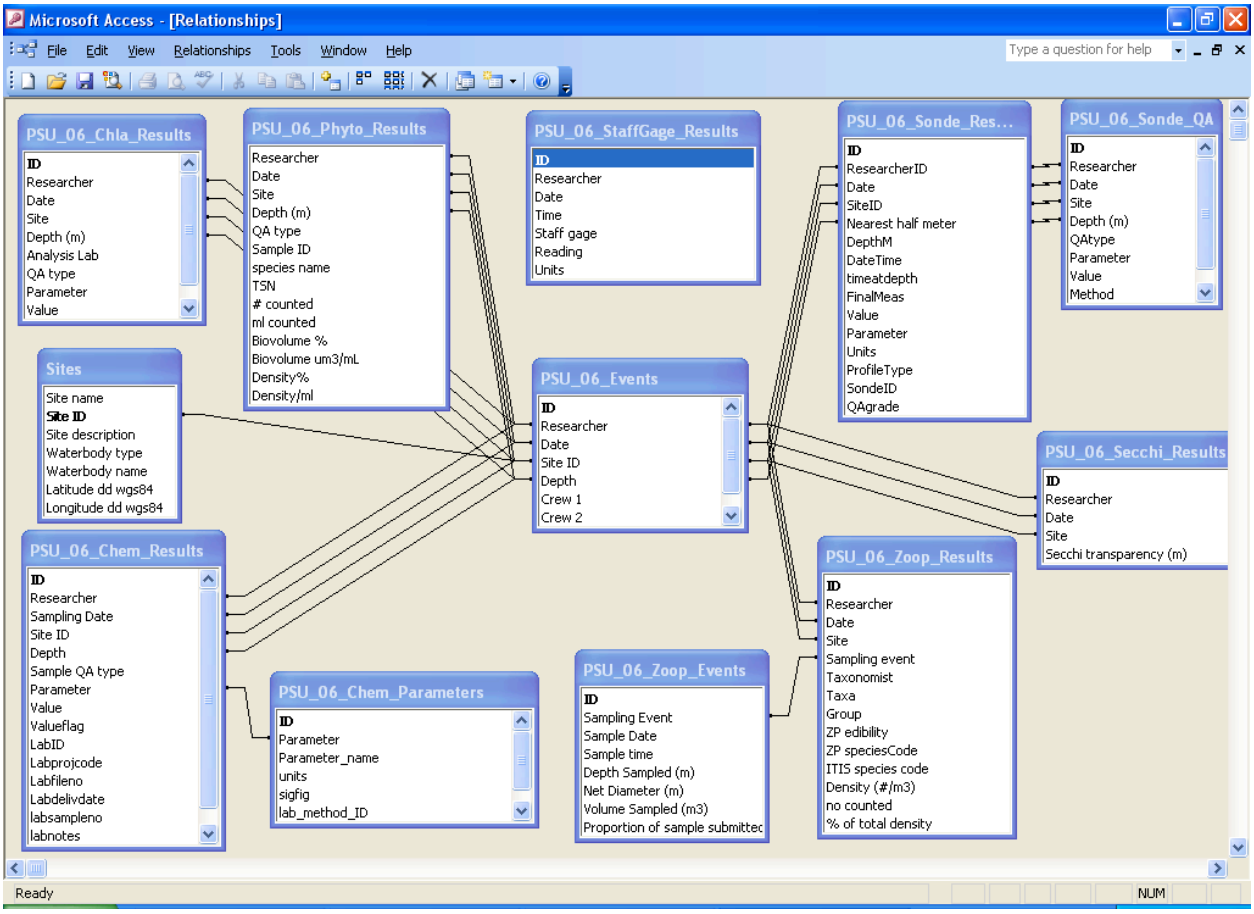

Figure 7. Microsoft Access database structure.

Section 3. Fish stocking index parameter trend assessment

Introduction

Water quality and the trout fishery in Diamond Lake have declined since the early 1990's, in parallel with the proliferation of tui chub (*Gila bicolor*), a small cyprinid fish species. Recent water quality problems included low dissolved oxygen concentrations, high pH values, dense algae, and toxigenic cyanobacteria blooms (Turner et al. 2006). These problems led to inclusion of the lake on Oregon's list of water quality-impaired water bodies (ODEQ 1998; ODEQ 2002; ODEQ 2006), public health advisories (ODHS 2006), and the loss of local economic vitality. Similar trends occurred in the 1940's and 1950's and were rectified by removing all fish from the lake with rotenone, a fish toxicant, and then restocking with trout (Dimick 1954).

Eilers et al. (2003) suggested two hypotheses for how tui chub degraded water quality in Diamond Lake. The first hypothesis was that the consumption of large zooplankton by tui chub had a cascading effect down the food chain that resulted in higher algal standing biomass and associated water quality problems. The second hypothesis was that consumption of large zooplankton by tui chub resulted in more rapid nutrient cycling and therefore higher nutrient availability to algae and thus higher algal growth and associated water quality problems. Eilers et al. (2003) suggested that tui chub are the primary cause of the decline in the trout fishery through exploitation competition with young trout for food, which lead to poor trout survival and growth rates.

In 2004 the USDA Umpqua National Forest authorized a plan to improve the fishery and water quality through removing all fish from the lake with rotenone and then restocking with trout (USDA FEIS, 2004). The lake was drawn down prior to the rotenone treatment in September 2006 to prevent outflow and downstream effects. Six thousand catchable size trout were stocked into the lake on April 26th, 2007 and fingerling trout are scheduled to be stocked to the lake during the spring of 2007.

Since trout are also zooplanktivores and can potentially impact water quality along the same pathways as tui chub (Eilers et al. 2001), trout fingerling stocking will be limited so as to have minimal negative impacts on water quality (Turner et al. 2006). Fingerling trout stocking levels prior to the tui chub invasion ranged from 300,000 to 500,000 per year (Figure 8). Eilers (2003) proposed a "Diamond Lake Fish Stocking Index" to evaluate the impact of fish stocking levels on the lake's water quality. The Fish Stocking Index consists of nine standardized water quality parameters and several trout health parameters that are sensitive to changes in zooplanktivore populations, mainly tui chub, that were derived from historic monitoring data. These parameters include: percent edible zooplankton, percent rotifers, algal biovolume, Secchi disc transparency, depth to anoxia, surface water dissolved oxygen saturation, surface water pH, chlorophyll a concentration, and percent amphipods. Eilers (2003) standardized each of these parameters to a scale of zero to ten; ten being the worst water quality condition; to allow for direct comparisons between parameters.

The purpose of this report section is to compare Fish Stocking Index parameter data collected by the Center for Lakes and Reservoirs (CLR) during the summer of 2006 with available prior monitoring data. Non-standardized parameters will be assessed because the emphasis of this report is to evaluate the individual parameters rather than the comparisons

between parameters. Benthic invertebrates (percent amphipods) and trout health will not be considered since the dataset was not available. All prior data were compiled by Eilers (Diamond Lake Database v5) and consist of data collected by Eilers (2003), Lauer (1979), ODEQ, ODFW, Salinas and Larson (1995), and Salinas (1996; 1997; 1998; 1999; 2000; 2001; 2002; 2003; 2004;2005).

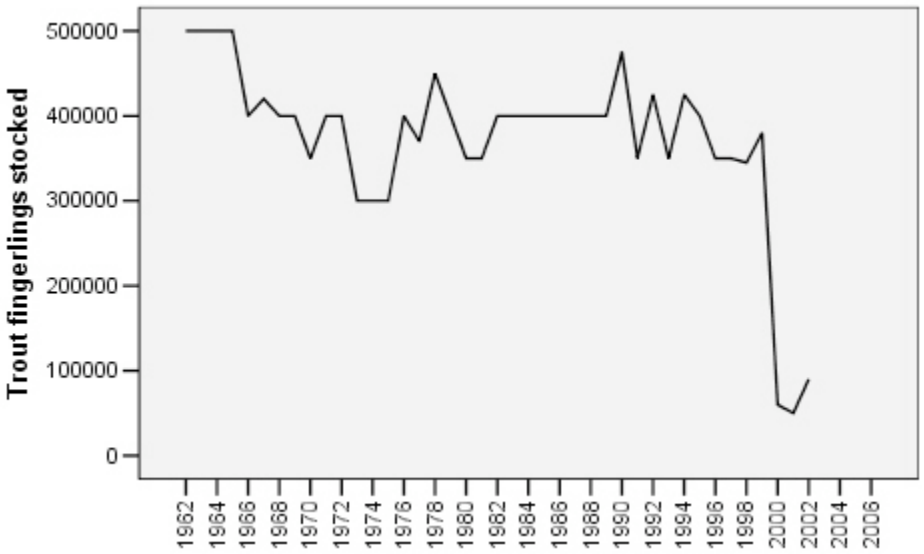

Figure 8. Number of trout fingerlings stocked in Diamond Lake from 1962 to 2002.

Percent edible zooplankton

Zooplankton larger than 1.25 mm, excluding cyclopoid copepods, are defined as edible by trout in Diamond Lake in samples analyzed ZP's Taxonomic Service (A. Vogel, pers. comm.). Rotifera are not counted as part of the total zooplankton population in percent edible zooplankton calculations. The 1.25-mm cutoff between edible and inedible zooplankton corresponds with the gill raker size of rainbow trout and observations of trout diet (Budy et al. 2005). Although this a functional rather than absolute definition of edible since smaller zooplankton (Budy et al. 2005) and cyclopoid copepods (Williamson 1991) can also be eaten by trout, percent edible zooplankton is a useful metric of zooplankton community size structure. Eilers (2003) proposed percent edible zooplankton as a sensitive response factor of fish grazing pressure on zooplankton. Edible zooplankton ranged from 34 to 91 percent of the total non-rotifer zooplankton population in 1994 and 1995, the early years of tui chub infestation (Figure 9). From 1995 to 2005, percent edible zooplankton was considerably lower, ranging from zero to 51 percent.

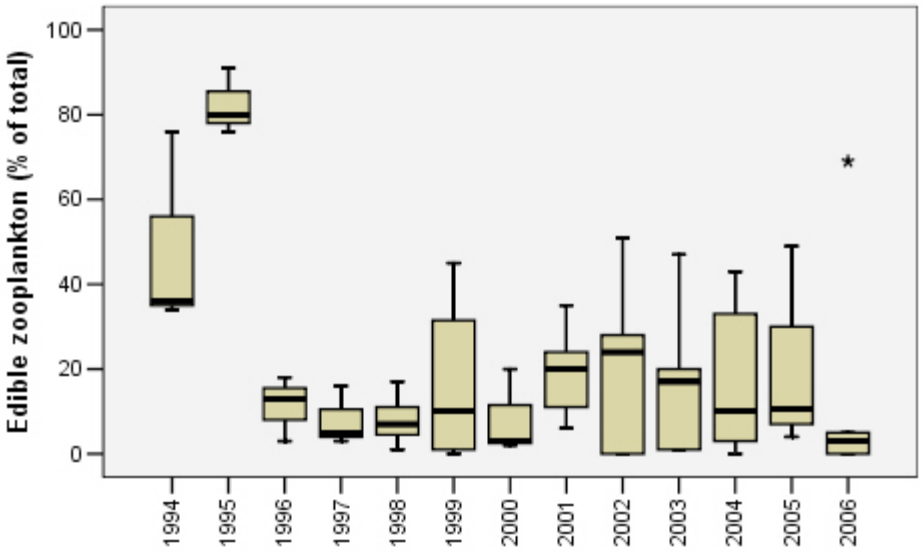

Figure 9. Percent of total non-rotifer zooplankton counted that are "edible" as defined by ZP's Taxonomic Service. Data are from Salinas and Larson (1995), Salinas (1996-2005), and this study (2007). Boxes are annual inter-quartile ranges (IQR), horizontal bars are medians, open circles are samples that lie 1.5-3 box lengths outside the annual IQR, asterisks are samples that lie greater than 3 box lengths outside the IQR, and whiskers are sample ranges exclusive of samples greater than 1.5 box lengths outside the IQR.

During the three CLR sampling events in 2006 prior to the rotenone treatment, percent edible zooplankton ranged from less than 5 percent on June 27th and July 17th to 69 percent on August 29th. Since rotenone is toxic to all gill-breathing fauna including zooplankton, (Finlayson et al. 2000) very low densities, regardless of size, were encountered on the two sampling events following treatment (Figure 10). Resting stages of zooplankton are not affected by rotenone (Chandler and Marking 1982); therefore, recovery of the zooplankton community is expected in 2007.

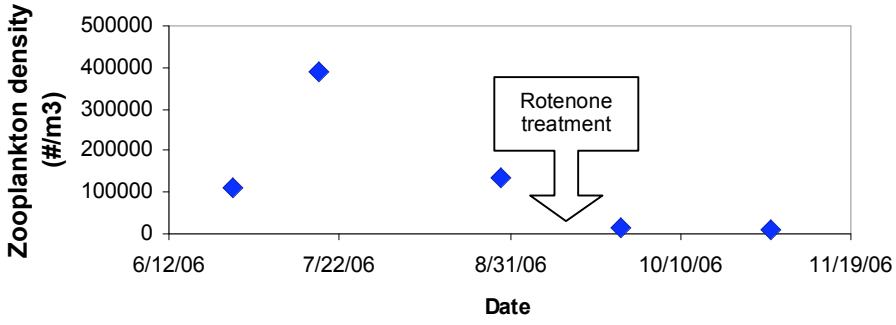

Figure 10. Total zooplankton density during 2006.

Percent rotifers

The percentage of the zooplankton community that consists of rotifers is thought to indirectly reflect fish grazing pressure in a manner inverse to percent edible zooplankton (Eilers 2003). Zooplankton collected from Diamond Lake since 2003, however, suggest that this relationship is more complex (Figure 11). Median annual percent rotifers was generally reduced after 2002 while no similar, but inverse, trend was evident in percent edible zooplankton. In addition, within year variance of percent rotifers was typically higher after 2002. Percent rotifers

measured in 2006 was similar to the previous four years and ranged from 40% on July 17th to 100% on September 26th, 12 days after the rotenone treatment. Such complex trophic relationships are not unexpected because trophic structure and species composition within trophic levels rarely exhibit exclusive top-down control or bottom-up control (Liebold et al. 1997).

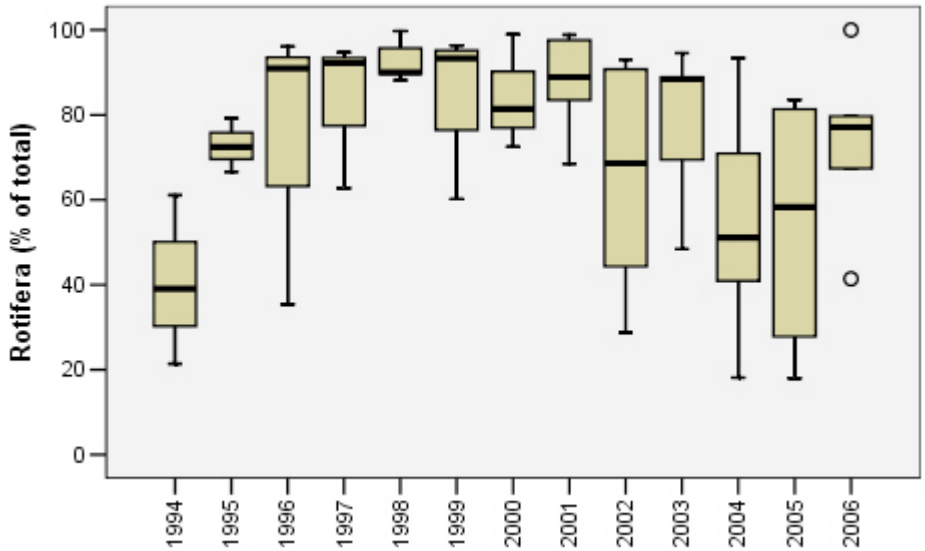

Figure 11. Rotifera as a percent of total zooplankton count. Boxplot descriptions are provided in Figure 9.

Phytoplankton biovolume

Phytoplankton biovolume was monitored in Diamond Lake from 1973 to 1977 and from 1989 to 2006. Unfortunately, the 1970s dataset does not appear to be directly comparable to the more recent dataset because the average biovolume for the recent pre-tui establishment dataset (early 1990's) is more than 100 times higher than the average biovolume in the 1970s dataset. This difference could be due to something as simple as differing units between the datasets, however, at this point the cause of the difference is unknown. As a result of the uncertainty, the 1970s dataset will not be included in this analysis.

Phytoplankton biovolume at the surface (1-m depth) of Diamond Lake increased substantially after 2000 (Figure 12). The average phytoplankton biovolume was 800,000 μm^3/ml between 1992 and 2000 and 1,970,000 μm^3/ml from 2001 to 2005; an increase of 250 percent. This trend does not correspond directly with the establishment of tui chub, but may represent a phytoplankton species shift that lagged behind the tui chub introduction. The percent of the phytoplankton community that consisted of *Anabaena spp.* also increased substantially in 2001 (Figure 13). Several *Anabaena* species have been identified in Diamond Lake including *A. flos aquae*, *A. circinalis*, *A. planktonica*, and *A. spiroides*. The most abundant species in Diamond Lake has been identified as *A. flos aquae*, however, taxonomic similarity with other *Anabaena* species precludes positive identification of *Anabaena* species over the course of long term monitoring.

Phytoplankton biovolume and percent *Anabaena* species composition were high during 2006, especially after the rotenone treatment. This was expected because of a lack of predation

by zooplankton and an increase in nutrient concentration from decomposition of tui chub carcasses.

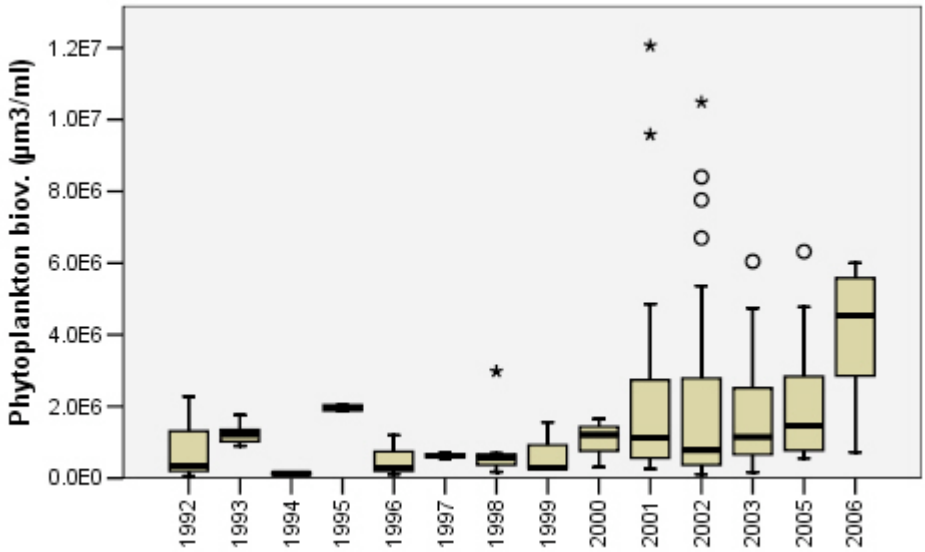

Figure 12. Phytoplankton biovolume at 1m. Boxplot descriptions are provided in Figure 9.

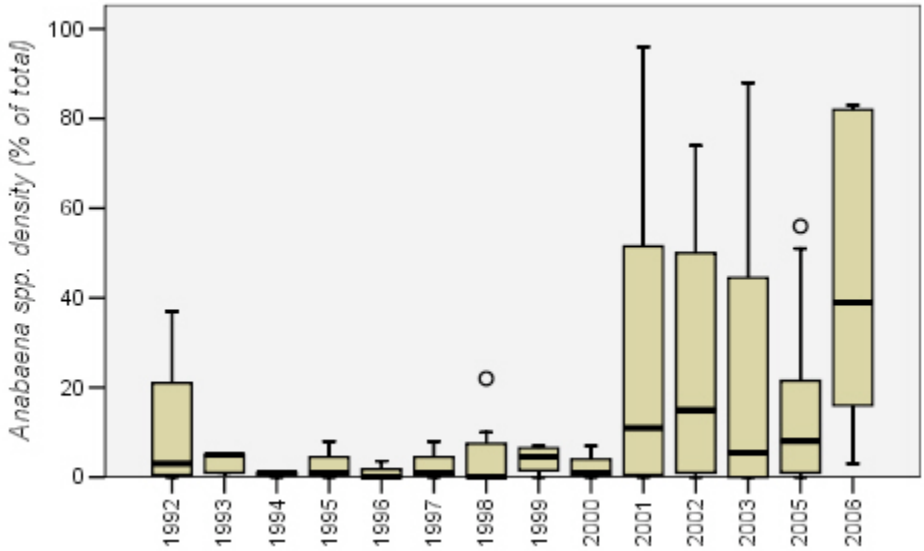

Figure 13. *Anabaena spp*. density as a percent of total algal density. Boxplot descriptions are provided in Figure 9.

Chlorophyll-a

Chlorophyll-a is an indirect measure of phytoplankton biomass. The complete historical chlorophyll-a dataset for Diamond Lake was not available; however, the median chlorophyll-a value at 1-m in 2006 was the highest of any of the available years (Figure 14). The highest chlorophyll-a concentration of the available data (61 µg/l) was measured October 31, 2006 (Figure 15). As noted above, high chlorophyll-a concentrations were expected after the rotenone treatment because of lake of a lack predation by zooplankton and an increase in nutrient concentration from decomposition of tui chub carcasses.

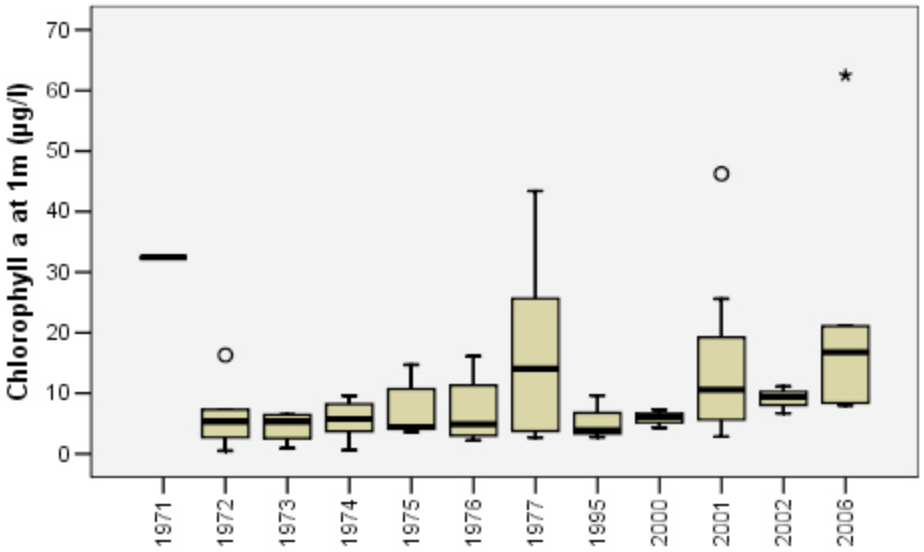

Figure 14. Chlorophyll a concentration at 1 m. Boxplot descriptions are provided in Figure 9.

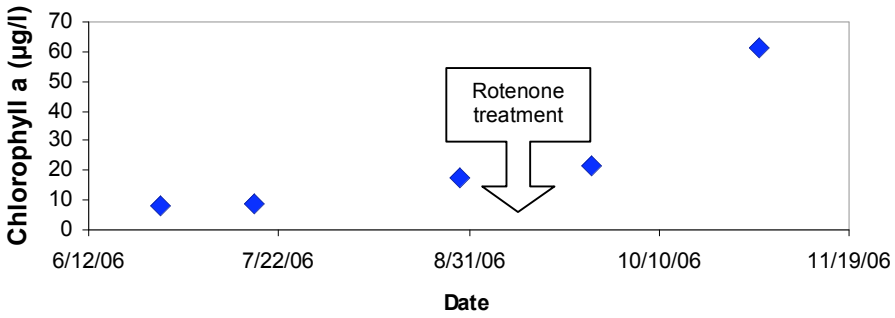

Figure 15. 2006 chlorophyll a concentration at 1 m.

Secchi disc transparency

Secchi disc transparency has been monitored at Diamond Lake since 1962 and is correlated with phytoplankton biovolume in Diamond Lake at 1 m (Pearson's ρ=0.81, $p<0.01$ for natural log transformed 1992 – 2003 data). This high correlation indicates that Secchi disc transparency in Diamond Lake is primarily determined by algal turbidity. Two recent downward shifts in Secchi transparency appear in the long term record: one after 1994 and one after 2000 (Figure 16). Transparency averaged 6.1 m during the 1962 to 1994 period; 4.5 m during the 1995 to 2000 period; and 3.0 m during the 2001 to 2003 period. Eilers (2003) hypothesized that the observed change in Secchi transparency was a result of the tui chub mediated food web changes. During 2006, Secchi disc transparency prior to the rotenone treatment ranged from 3.6 m on June 27th to 1.7 m on August 29th. After the rotenone treatment Secchi disc transparency declined to 1.1 m on September 26th and 0.9 m on October 31st. These changes are consistent with the increase in phytoplankton biovolume and chlorophyll-a.

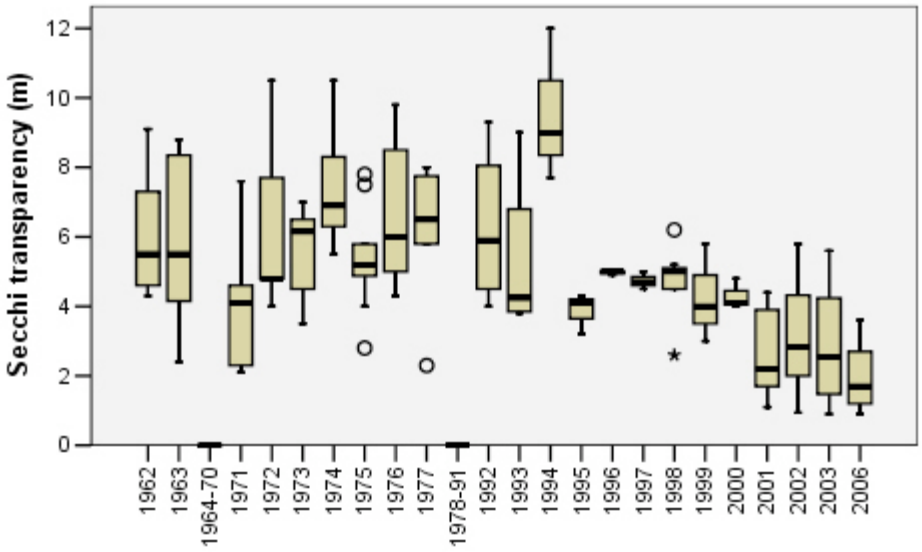

Figure 16. Secchi disc transparency. Boxplot descriptions are provided in Figure 9.

Hypolimnetic dissolved oxygen

Dissolved oxygen in the hypolimnion of Diamond Lake was measured by Lauer (1979) from 1971 through 1977 at 13 m, approximately 3 m above the sediment surface at the DLA site. More recent measurements were made at multiple hypolimnetic depths. Low summertime hypolimnetic dissolved oxygen concentrations were common in recent years (Figure 17). From 2000 to 2003, July and August concentrations at DLA site were less than 2 mg/l at 13 m. 2006 concentrations can not be directly compared with previous year's measurements at 13 m since the lake was drawn down; however, concentrations at 10 m were less than 1 mg/l during the July and August sampling events.

The duration of stratification and the amount of organic material supplied to the hypolimnion are the primary factors that influence year-to-year variation in hypolimnetic dissolved oxygen within a lake (Cornett and Rigler 1979). The duration of stratification is determined by climatic factors while the supply of organic material is determined by nutrient loading and food web structure (Lehman 1988). Eilers (2003) suggested that tui chub mediated food web changes were the driving force behind the observed decrease in the depth to anoxia. There was a lag between the establishment of tui chub and severe hypolimnetic dissolved oxygen depletion observed from 2000 to 2003. The mechanisms behind this lag are not well understood.

Although many of the tui chub killed during the rotenone treatment in 2006 were removed from the lake, the decomposition of chub carcasses that remained in the lake consumed oxygen in the water column. The lake was not stratified during treatment, or during the September 26th sampling event following the treatment; therefore exchange with the atmosphere and photosynthetic oxygen production prevented severe dissolved oxygen depletion throughout the water column. Chub carcasses may continue to contribute biological oxygen demand in 2007 and thus hinder the likely positive response of hypolimnetic dissolved oxygen to food web manipulations.

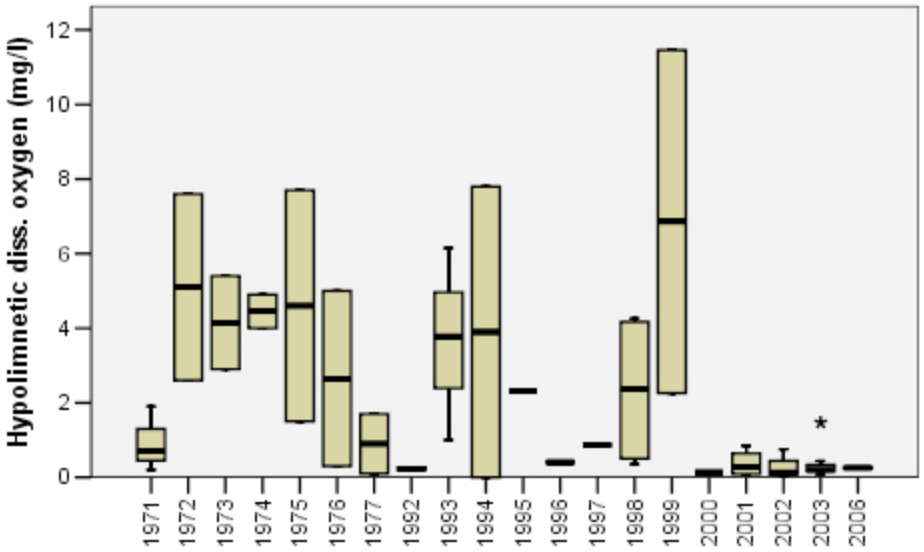

Figure 17. Hypolimnetic dissolved oxygen concentration during the months of July and August. 1971-2003 data are concentration at 13 m while 2006 values are concentrations at 10 m. Boxplot descriptions are provided in Figure 9.

Mixed surface layer dissolved oxygen saturation.

Saturation of dissolved oxygen in the mixed surface layer of lakes is determined by water temperature and air pressure. Deviations from saturation occur daily based on the balance between primary production and respiration. During the day, production exceeds respiration causing an increase in dissolved oxygen; during the night, respiration exceeds production causing a decrease in dissolved oxygen. The degree of deviation from saturation is a function of the magnitude of production and respiration and rate of equilibration with the atmosphere. Therefore, there is a higher likelihood that a single measurement of mixed-layer dissolved oxygen will deviate from saturation in a productive lake than in an unproductive lake, which will result in higher annual variation is dissolved oxygen saturation. Variation is dissolved oxygen saturation at 1m in Diamond Lake was higher from 1999 through 2003 than prior to 1999 (Figure 18). It is expected that variation in surface water dissolved oxygen concentration will decrease with the food web changes in 2007.

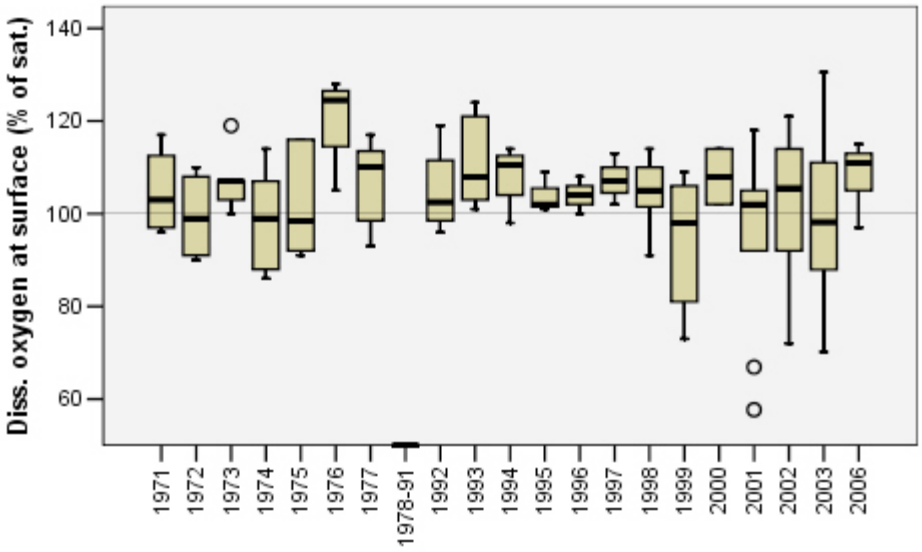

Figure 18. Dissolved oxygen concentration at the lake surface. Boxplot descriptions are provided in Figure 9.

pH

Equilibrium pH in the mixed layer at the surface of a lake is primarily determined by the carbonate alkalinity of the lake. Equilibrium pH at Diamond Lake is roughly 7.7 pH units. Like dissolved oxygen concentration, the divergence of pH from equilibrium is a result of the balance between primary production and respiration. High primary production can consume carbon dioxide faster than the carbonate system can equilibrate resulting in elevated pH values. Conversely, respiration can generate carbon dioxide faster than the system can equilibrate resulting in depressed pH values. In Diamond Lake, mid-day surface pH values have trended higher since the early 1970's (Figure 19). Unfortunately, the quality of the 2006 monitoring data is questionable (see data quality, report section 1) and cannot be reliably interpreted.

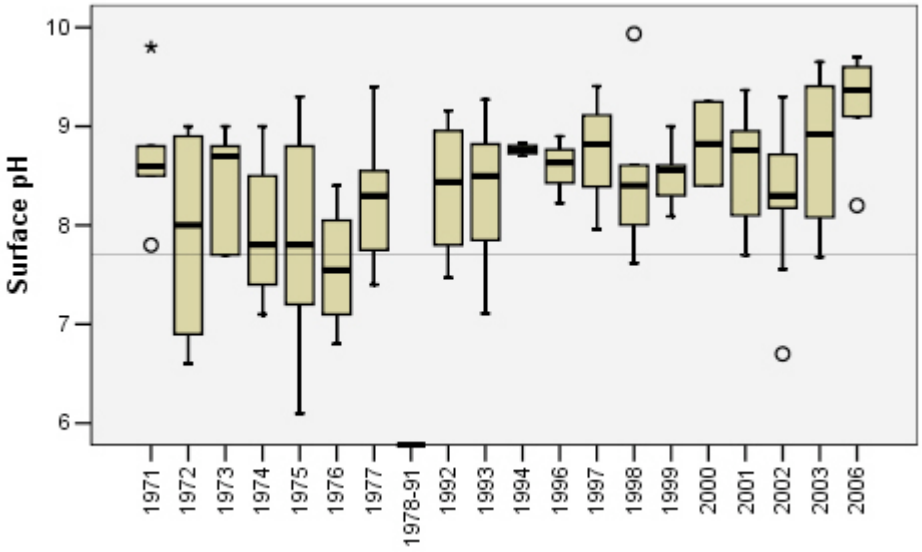

Figure 19. pH at the lake surface. The horizontal line is a rough estimate of equilibrium pH. Boxplot descriptions are provided in Figure 9.

Primary Productivity

Primary productivity is a measure of the production of organic material through photosynthesis. A report by The Cascade Research Group on primary productivity measured during 2006 is included as Appendix A. Depth integrated productivity during 2006 was similar to productivity during the period from 1997 to 2005 (Figure 20).

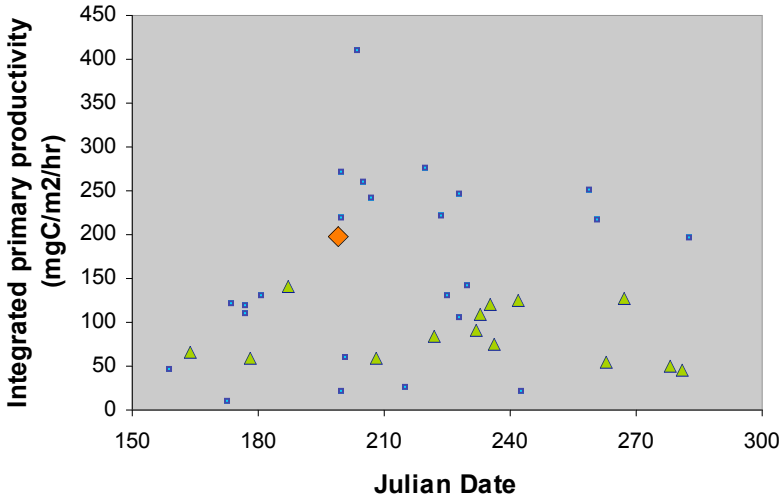

Figure 20. Water column integrated primary production at site DLA. Data are from 1992-1996 (triangles), 1997-2005 (circles), and 2006 (diamond). Julian dates 150 and 300 correspond to early June and late October respectively.

Summary and conclusions

The quality of data collected during 2006 was good with two exceptions – there were detectible levels of dissolved organic carbon in field blank samples, and pH measurements were inaccurate. These problems have been rectified through acid washing DOC filters and replacement of the pH probe. All data were entered into an Access database.

As expected, water quality in Diamond Lake was poor during 2006, especially after the rotenone treatment. Over the longer term, several of the parameters used in the "Fish Stocking Index" appear to be particularly sensitive indicators of zooplanktivory and are therefore most useful for tracking the impact of trout stocking levels on water quality. These parameters include percent edible zooplankton, phytoplankton biovolume, Secchi disk transparency, and hypolimnetic dissolved oxygen. The composition of the phytoplankton community, especially the percent *Anabaena* species, is also sensitive to zooplanktivory. Although the percent amphipods in the benthic community was not assessed in this report, Eilers (2003) found that this parameter was very responsive to tui chub proliferation. Eilers (2003) also suggested that maximum depth of macrophyte colonization was influenced by tui chub. Macrophyte depth distribution is primarily determined by light penetration, and reflects a long-term response to light; as such, it may better integrate the growing season light environment better than a series of discrete Secchi disc measurements. Primary productivity also appears to be sensitive to the food web changes in Diamond Lake. The percent rotifers, surface water dissolved oxygen, chlorophyll-a, and pH parameters appear to be less sensitive to zooplanktivory.

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Appendix A. Diamond Lake Primary Productivity Survey Summer, 2006

Diamond Lake Primary Productivity Survey Summer, 2006

Report CAS-0107

Produced for

The Umpqua National Forest and Portland State University

January, 2007

by

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Method: Primary Productivity (Submitted by John Salinas)

The rate of primary productivity was measured in Diamond Lake on July 18, 2006. Water samples were taken from the DLA station at the surface and every two meters to the bottom at Diamond Lake for incubation. The samples were placed in paired dark and clear bottles to be inoculated with C-14 and incubated *in situ* for 3.87 hours beginning at 9:40 AM. Duplicates for quality assurance were taken at the 2, 6 and 10 meter depths. A volume of 100 mL was then filtered using 0.45 μM pore Millipore filters from a 250 mL sample and the filters checked for the uptake of the radioactive tracer; the more activity on the filter, the greater the carbon uptake, and the higher the rate of primary productivity in the lake. Sample filters were delivered to the Oregon State University Radiation Center in Corvallis for determining the activity of each. Productivity estimates for each depth were calculated (Wetzel, 2000).

The CCAL pH values were used in the productivity calculation following historical protocol. The alkalinity determinations made by CCAL were also used in the calculations of productivity. The only field measurement used in this calculation was the *in situ* temperature measurement and is only available in the field.

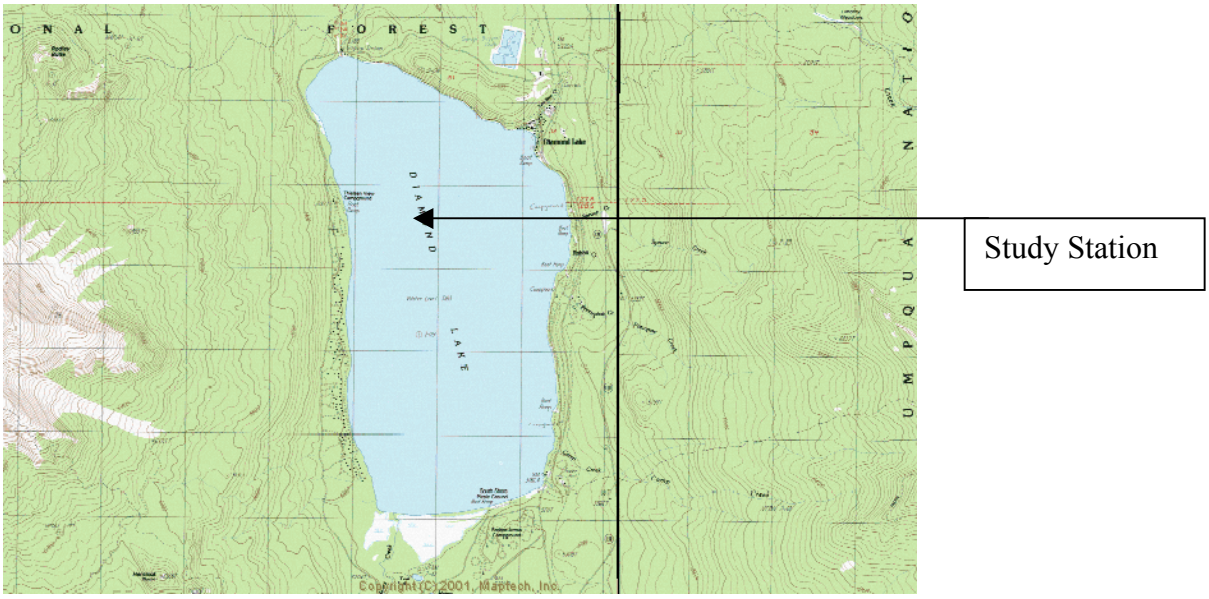

Figure 1. Diamond Lake surveyed during the 2006 summer season.

Results: Primary Productivity

The primary productivity of Diamond Lake was determined once during the summer of 2006. The productivity calculation requires the counts per minute (from the filter sent to the OSU Radiation Center), the *in situ* temperature, the in situ pH, and the alkalinity (CCAL). During the July 18 field trip, Rich Miller from PSU also collected samples at the same DLA station at 1, 8, and 10 meters, however he was on the lake on 17 July 2006. Using the in situ pH values an integrated productivity was calculate to be 197.1 mgC/m2/hr. The integrated productivity was also calculated with the CCAL pH values giving a value of 217.7 mgC/m2/hr.

In July three light bottles and three dark bottles were placed at 2, 6, and 10 meters depth as quality assurance tests. The three independent samples deviated from 1.23 to 2.57% and further suggest that primary productivity estimates are variable with an average percent deviation of about 2.0%.

Table I. Results of Paired Productivity Bottles, Diamond Lake, 18 July 2006

Depth (m)	Prod	Avg Prod	Average Deviation	% Avg Dev
2	37.52			
2	38.45	37.99	0.466	1.23
6	14.08			
6	14.74	14.41	0.329	2.28
10	1.66			
10	1.74	1.70	0.044	2.57

In July the peak productivity was at 2 meters depth, with 38 mgC/m^3/hr (Figure 2). It declined sharply until a depth of 8 m and remained very low to the bottom of the lake, about 11 m. The July values of productivity remain high since 2001. Except for one date in August 1997, since 2000 higher levels of productivity continue to be observed. Most July profiles since 2000 definitely belong to this greater set of values. This upper set of productivity profiles appears to stand above 200 mgC/m^2/hr (Figure 3)

The integrated productivity for July since 2002 have been steady and between 200 and 410 mgC/m2/hr. These values can be set in an historic perspective (Figure 4). If the July productivity profiles are viewed, there is a noticeable increase in productivity since this study began in 1992 (Figure 4). These profiles also indicate that productivity in July has been steady and between 275 and 195 for the past four years. This past year the productivity was lower than that measured in the past seven years for July. This may have been caused by the decrease in lake depth caused by the drawdown in preparation for the fish eradication management completed in September 2006.

Table II. Productivity at Diamond Lake, 18 July 2006

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depth	lake	date	Prod	Int Prod	
			mgC/m3/hr	mgC/m2/hr	
0	DIAMOND	18-Jul-06	18.78		
2	DIAMOND	18-Jul-06	38.45	57.2	
4	DIAMOND	18-Jul-06	30.81	69.3	
6	DIAMOND	18-Jul-06	14.74	45.5	
8	DIAMOND	18-Jul-06	3.31	18.0	
10	DIAMOND	18-Jul-06	1.74	5.1	
12	DIAMOND	18-Jul-06	0.25	2.0	
		Total		**197.1**	**mg C/m2/hr**
		CCAL pH used		217.7	**mg C/m2/hr**
	Dups				
2	DIAMOND	18-Jul-06	37.52		
6	DIAMOND	18-Jul-06	14.08		
10	DIAMOND	18-Jul-06	1.66		

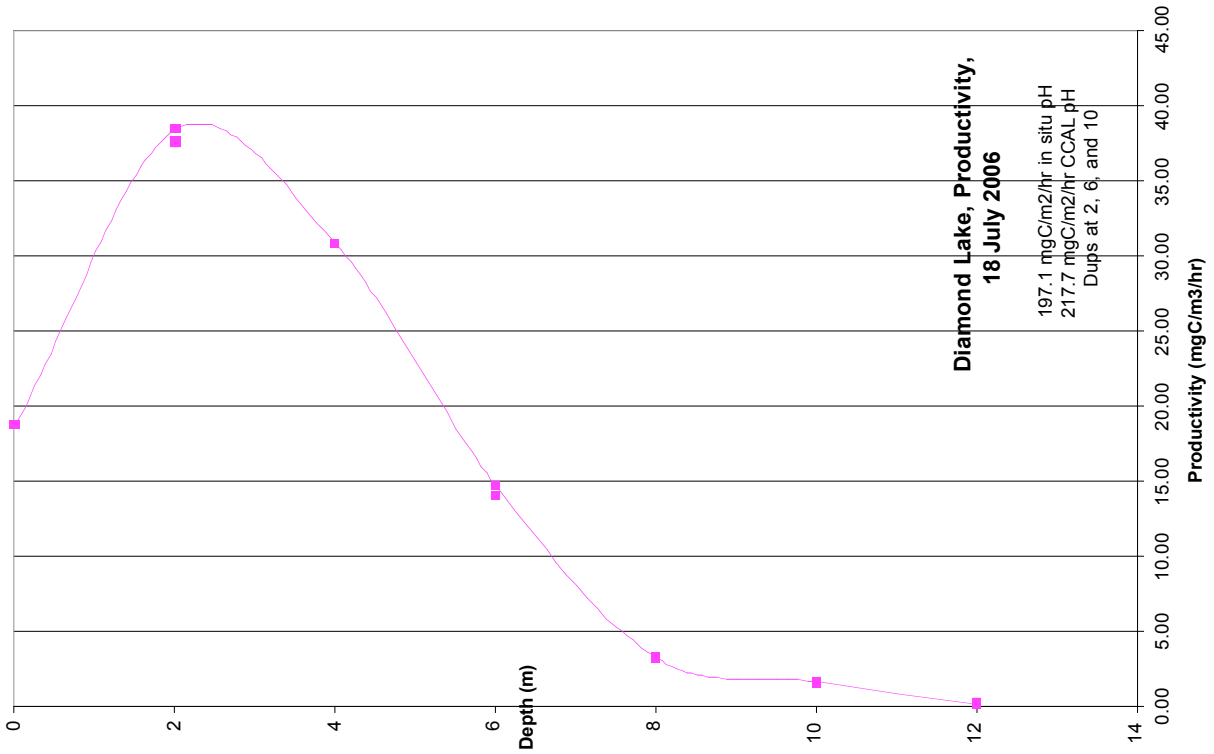

Figure 2. Diamond Lake, primary productivity profiles, 18 July 2006.

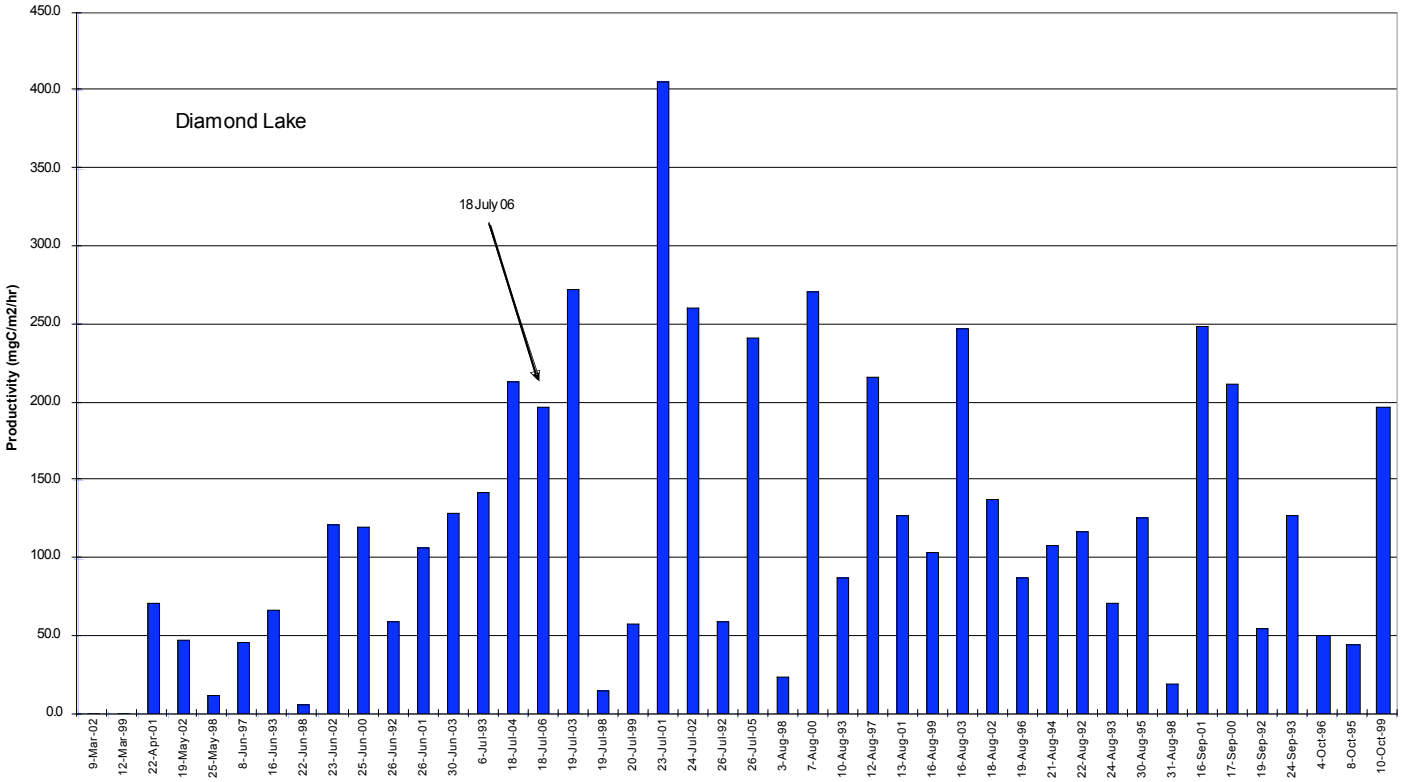

Figure 3. Historic Diamond Lake primary productivity.

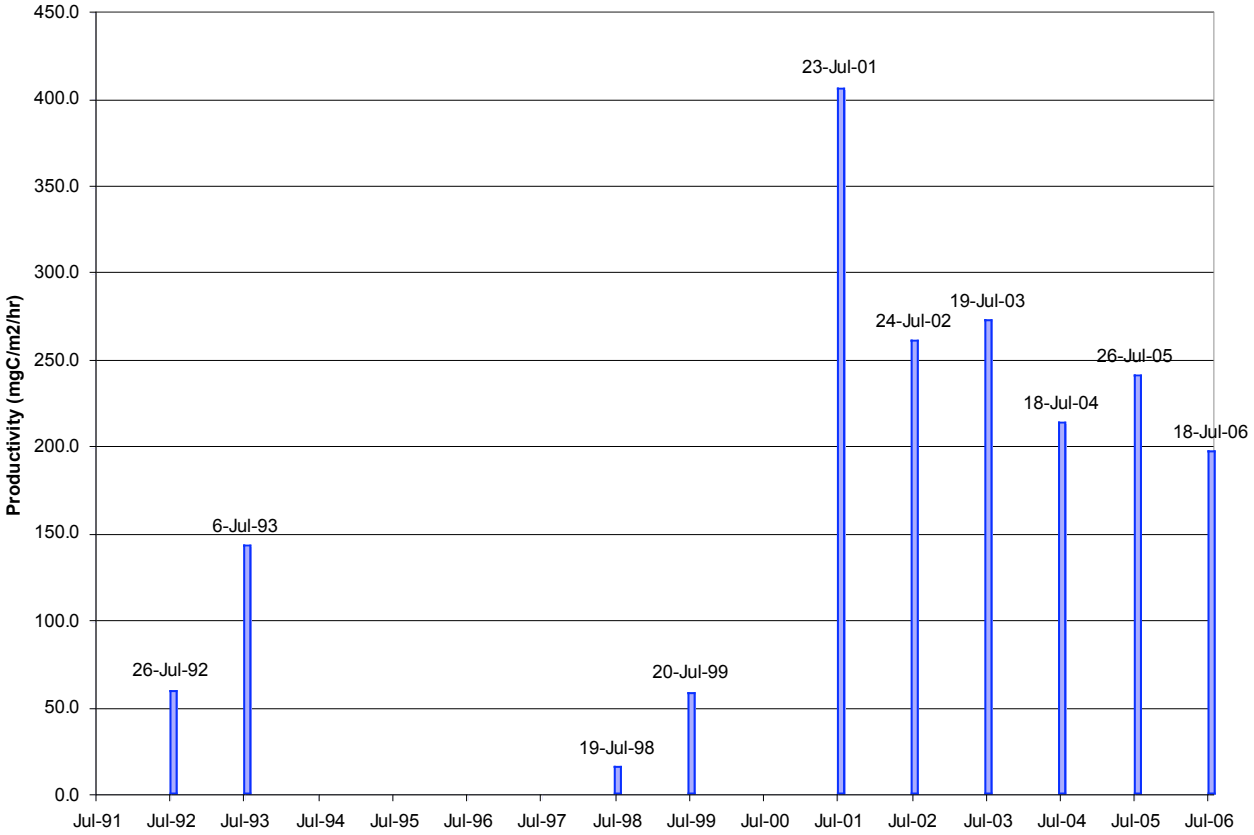

Figure 4. Diamond Lake historic productivity, July.

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